CCD Time-Series Photometry of Faint Astronomical Sources

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Abstract

Using CCDs to obtain time-series light curve information is an increasing area of interest in astronomy. For brighter, high signal-to-noise sources, the data collection and reduction procedures are very robust and easy to use. However, for fainter, low signal-to-noise objects we must resort to new methods. These include the use of optimum data extraction techniques, a fuller understanding of the CCD itself, and a more complete error model. This paper will provide a brief introduction to CCD time-series photometry and then explore the above new methods in relation to real observational situations.

1. Introduction

The recent astronomical literature contains many papers in which CCD time-series observations have been used. Howell and Jacoby (1986) were the first to provide a recipe for this type of work and they alerted the user to some of the parameters to consider when using CCDs as time-series photometers.

The basic idea of time-series photometry is to collect a temporally contiguous set of CCD frames of a particular source or sources, and to do this with as short a time resolution as possible. Typical values for current time resolutions are 5-30 seconds up to 5-10 minutes for sources of 14^{th} to 22^{nd} magnitude when using 1 to 2.5-m telescopes. The set of CCD frames are then reduced in the standard way (e.g., Gilliland 1992), and is likely to include bias subtraction, flat fielding, etc.

The reduced frames are now ready for photometric reductions to be performed. Any number of 2-D aperture photometry methods can be applied at this point. A few of the most popular are discussed in Adams (1980), Stetson (1987), and Howell (1989). Errors can then be assigned to each datum and the photometric results corrected for extinction and color terms, i.e., standard photometric reduction procedures. Finally, light curves can be produced (either absolute or differential) and the analysis of these data for variability or periodicity performed. Howell (1992) gives a detailed review of time-series CCD photometry.

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2. Bright vs. Faint Sources

The signal-to-noise (S/N) for a point source imaged on a CCD is given by (Howell 1992),

$$\frac{S}{N} = \frac{N_*}{\sqrt{N_* + n_{pix}\left(1 + \frac{n_{pix}}{n_{BG}}\right)\left(N_S + N_D + N_R^2 + G^2\sigma_f^2\right)}} \tag{1}$$

We can define a bright source as one in which the following condition is true,

$$\text{if } N_* \gg n_{pix}\left(1 + \frac{n_{pix}}{n_{BG}}\right)\left(N_S + N_D + N_R^2 + G^2\sigma_f^2\right) \tag{2}$$

and a faint source is one for which

$$N_* \ll n_{pix}\left(1 + \frac{n_{pix}}{n_{BG}}\right)\left(N_S + N_D + N_R^2 + G^2\sigma_f^2\right) \tag{3}$$

These two definitions are guides for us in our usage of the terms bright (high S/N source) or faint (low S/N source). They are however, relative terms which depend on the magnitude of the source, the telescope used, the CCD characteristics, the sky brightness, etc. The user must decide for herself which objects are bright and which are faint. Figure 1 shows example models (see Merline and Howell 1992) of a high S/N source and a low S/N source. Figure 2 shows the range of S/N compared with the ratio of N_* to p where $p = n_{pix}\left(1 + \frac{n_{pix}}{n_{BG}}\right)\left(N_S + N_D + N_R^2 + G^2\sigma_f^2\right)$ for a 1-m telescope. The other specifics about the telescope, sky, and CCD are listed in the figure. The models in Figure 1 used these same listed parameters. Note that in Figure 2, near 15th or 16th magnitude, there is a slope change in the curve which may be useful in deciding between bright and faint sources in this particular plot.

3. Optimum Data Extraction and Error Contributions

If one carefully examines equation (1) given above for the S/N of a point source, it is apparent that for a given telescope-CCD combination, the only parameter directly under the user's control is the value n_{pix}. Thus, if the user can decrease the relative contribution of n_{pix}, the S/N of a given observation will be increased. Howell (1989) discusses this at length and finds that while standard 2-D aperture extraction uses an extraction radius of ~3 FWHM, an optimum radius for data extraction occurs at near 0.5 FWHM. This radius is optimum in that it provides the largest S/N measurement for a point source, although caution must be exercised to assure the source is not undersampled and the extraction software handles partial pixels in a flux-conserving, correct manner. Increases to the S/N of 20-50% are realized by use of these optimum apertures. DaCosta (1982) and Stetson (1990) also discuss small aperture data extraction.

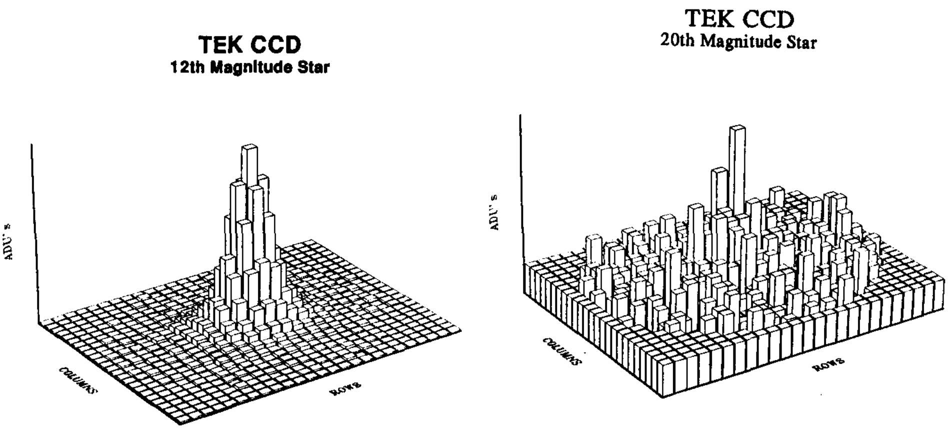

Figure 1: Models using a TEK CCD and a 1-m telescope of a bright (high S/N) and a faint (low S/N) point source. The techniques described in the paper are aimed at obtaining good photometric information on time-series CCD observations of these fainter type sources.

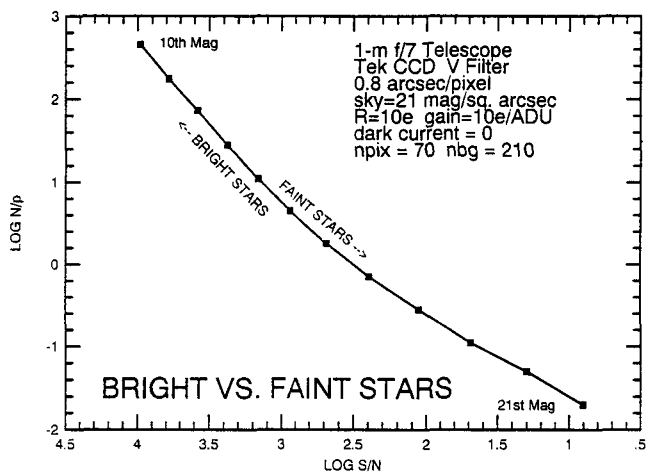

Figure 2: The S/N [see eq. (1)] plotted against the ratio of N_* to p for a range of point source brightness. The telescope/instrument characteristics are given on the figure.

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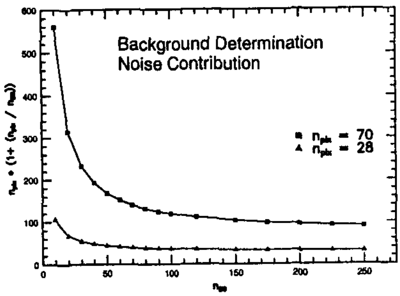

Figure 3: The relative error contribution of the number of background pixels used. Note how the optimum case requires fewer pixels and always has a smaller error contribution.

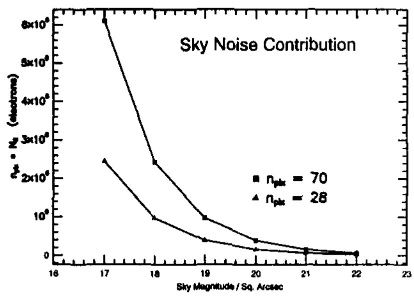

Figure 4: The relative error contribution of the sky noise. For less than ideal dark sites on nights when the moon is present, the optimum aperture case provides far less of an error contribution.

The three error terms, which we collectively called p in the last section, will now be examined separately. In each case, we compare the error term contribution of standard 2-D aperture extraction to that obtained by the use of optimum 2-D aperture extraction. All the plots in this section are based on the CCD and telescope characteristics listed on Figure 2.

First is the determination of the background. This is usually done by extracting some number of pixels which appear free of any faint stars, galaxies etc. and away from any obvious CCD imperfections. Figure 3 shows the relative contribution of the term $\left(1+\frac{n_{pix}}{n_{BG}}\right)$ over a range in the number of background pixels used. In general, using $n_{BG} \geq 3n_{pix}$ provides essentially the best possible background determination. In the optimum extraction case, the use of 60% less background pixels yields, in all cases, a smaller noise term.

We next examine the sky noise contribution to the error budget. Figure 4 shows this noise term over a range of sky brightness. Again, we see that the optimum extraction case provides a significantly lower error contribution, particularly for brighter sky backgrounds.

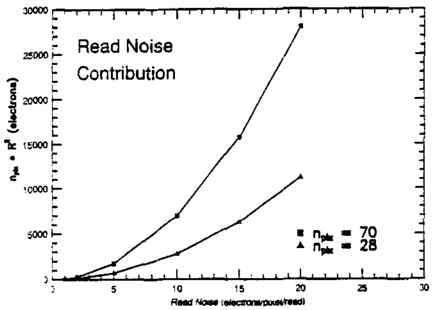

Figure 5: The relative error contribution of the CCD read noise. Most modern CCDs have very low read noise, thus this term becomes less important.

Finally, the read noise contribution is shown in Figure 5. This term is simply a scaled factor based on the read noise of the particular CCD used. For the newer, low read noise CCDs, the difference between standard and optimum data extraction is small for this term.

4. Magnitude Error and Observational Example

Using equation (1) given above for the S/N of a point source, the expected variance in flux for a source can be written as (see Howell et al. 1988)

$$\sigma_F^2 = \frac{N_* + p}{t^2} \left(e^-/\mathrm{sec}\right)^2 \tag{4}$$

and the error, in magnitudes, for a given observation will be

$$\sigma_{mag}^2 = (2.5 \log e)^2 \frac{\sigma_f^2}{f^2} \tag{5}$$

where $f = N_*/t$. Therefore,

$$\sigma_{mag} = \frac{1.0857\sqrt{N_* + p}}{N_*} \tag{6}$$

As an example of the use of optimum data extraction and the use of the magnitude error equation above, Figure 6 shows an example CCD time-series light curve of a V=19.7 variable star. The data were obtained with a 1.8-m telescope and a TI CCD. Each point represents a measurement from a single CCD frame of integration time 297.6 μFortnights (i.e., 360 seconds). The top curve was extracted using a standard aperture of radius 2.4 FWHM while the bottom curve used an optimum aperture of 0.64 FWHM. The bottom curve was shifted downward by about 1 magnitude for clarity. The average 1 σ error for the standard extracted curve is 0.087 mag while the optimally extracted data have an average 1 σ error of 0.055 mag.

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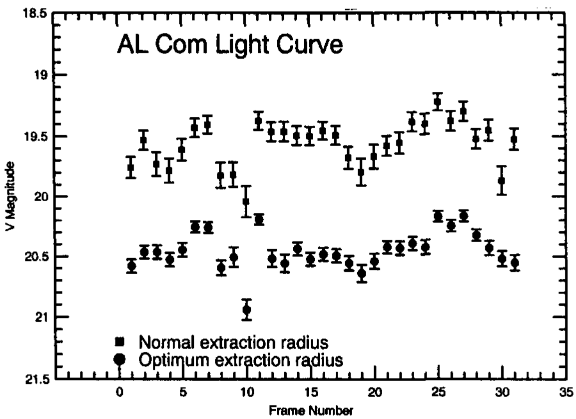

Figure 6: A representative CCD light curve of a V=19.7 magnitude variable star. See the text for details.

References:

Adams, M., Christian, C., Mould, J., Stryker, I., and Tody, D. 1980, *Stellar Magnitudes from Digital Pictures* (Tucson, AZ: Kitt Peak National Observatory).

DaCosta, G.S., Ortolani, S., and Mould, J. 1982, *Ap.J.*, **257**, 633.

Gilliland, R.L. 1992, *Astronomical CCD Observing and Reduction Techniques*, ASP Conference Series, Volume 23, 68.

Howell, S.B., and Jacoby, G. 1986, *PASP*, **98**, 802.

Howell, S.B. 1992, *Astronomical CCD Observing and Reduction Techniques*, ASP Conference Series, Volume 23, 105.

Howell, S.B., Mitchell, K.J., and Warnock III, A. 1988, *A.J.*, **95**, 247.

Howell, S.B. 1989, *PASP*, **101**, 616.

Merline, W.H., and Howell, S.B. 1992, in *Astronomical Data Analysis Software and Systems I*, ASP Conference Series, Volume 25, 316.

Stetson, P.B. 1987, *PASP*, **99**, 191.

Stetson, P.B. 1990, *PASP*, **102**, 932.

Discussion

E.F. Milone: *Variable star observers cannot always be choosey about the air mass of their observation. Do you worry about effects of image refraction at larger air masses? Also, do you select the optimum aperture at the time of your observation?*

Howell: I have not seen any effects from air mass for my differential photometry using objects on the same CCD frame. One can pick an optimum aperture for each object on a frame by frame basis.

D. O'Donoghue: *What is your limiting magnitude on a 1-m telescope with a few minute exposure?*

Howell: In a one minute exposure at a good S/N your limit will be something like 17th magnitude. If you are willing to increase your integration time a bit, you'll be able to get to 20th magnitude or so.

E. O'Mongain: *How do you center your apertures?*

Howell: For standard 2-D aperture data extraction, I use simple X-Y centroiding. For the optimum aperture extraction, I use more sophisticated schemes being very careful about under-sampling.

W.H.S. Monck: *You may be aware that Stephen Dixcon and I made the first electrical measurements of starlight in 1892, in Dublin, using George Minchin selenium photovoltaic cell. It is certainly impressive to see what can now be obtained with CCD photometry. Therefore, could you give me an example of just how sensitive a CCD is compared with my selenium cell?*

Howell: Well, to observe the same star which you did on your telescope, one would need to attenuate the incoming flux by first passing the light through roughly a pint of Guinness!

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